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MODELING COMPLEX MANUFACTURING SYSTEMS USING SIMULATION

Bernard J. Schroer
Johnson Research Center
University of Alabama in Huntsville
Huntsville, AL 35899

Fan T. Tseng
College of Administrative Science
University of Alabama in Huntsville
Huntsville, AL 35899

ABSTRACT

This paper presents an approach in simulating complex manufacturing systems. The approach is founded on developing several general purpose simulation generators for an assembly station, a manufacturing cell, and an inventory transfer function. These simulation generators can then be linked together to create a model of a complex manufacturing system. A typical manufacturing system is modeled using these simulation generators and the results summarized.

1. INTRODUCTION

Applying discrete event simulation techniques for modeling manufacturing and production systems have been performed for many years (Gordon 1975) (Schriber 1974). In fact, most of the common discrete event simulation languages have been implemented on the major computer mainframes.

In recent years there has been a renewed interest in using simulation for studying manufacturing and production systems. There are a number of factors which have contributed to this renewed interest. One of the major factors has been the wide introduction and acceptance of microcomputers. These microcomputers have capabilities that for many years were only available on large mainframes.

A second factor for this renewed interest is the conversion of the common simulation languages for the microcomputer. Furthermore, a variety of new simulation languages have also been written. A survey of these simulation languages is given in Simulation (1986 and 1987). Coupled with these traditional simulation languages has been the recent introduction of several new simulation languages specifically designed for manufacturing simulation such as SIMAN (Pegden 1985).

A third factor contributing to this renewed interest has been the adding of very elaborate computer graphics to many of the simulation languages. This graphics capability is most noticeable on the microcomputer based simulation languages. For example, SIMAN (Pegden 1985), and GPSS/PC (Minuteman 1986) have elaborate graphics capabilities.

In addition to these factors, the excitement generated by Artificial Intelligence, or AI, as a simulation assist has refueled interest. For example, research is being conducted on interfacing natural languages with simulation (Ford 1986), simulating a manufacturing system using an expert system assist (Elmaghraby 1985) and building expert systems for system analysis (Haddock 1987). Also, several AI software developers are currently writing simulation development tools such as SIMKIT (Intellicorp 1986) and Carnegie Group's Inc. SIMULATIONCRAFT (1987).

With all these simulation advances, problems still exist in making the modeling process simpler and faster, especially for the less trained simulationists. One approach in simplifying the simulation process is to develop a set of general purpose routines or macros that can serve as the building blocks in a simulation. In this paper these routines are called generators. This paper presents an approach to building several of these generators for simulating manufacturing systems.

2. MANUFACTURING SYSTEM

Most manufacturing systems can be represented by the following three simulation generators: an assembly station generator, a manufacturing cell generator and an inventory transfer generator. In addition to the generators, stock points are required to indicate Work In Process (WIP) inventory. Whirlygigs may be required for transferring the WIP between the stock points.

2.1 Assembly Station Generator

The assembly station generator is representative of a typical assembly station. Items arriving at the station first wait in a queue until the assembly station becomes available. Once an item seizes the assembly station, it waits in another queue until a part at the assembly cell stock point is available to be added to the item. An elapsed amount of time is then simulated while the part is added to the item. The inventory at the stock point is then reduced by one and the item releases the facilities. Before exiting the generator a check is made to determine if a subassembly line is feeding the station. If so, the transaction exits the subroutine. If not, a second check is made to determine if the inventory is empty at the stock point. If a cart is empty, a signal is sent indicating an empty cart. If not, the transaction exits the subroutine. It should be noted that the inventory at the stock point can be defined in terms of number of carts with a fixed number of parts per cart. A signal is sent when a cart is empty.

2.2 Manufacturing Cell Generator

The manufacturing cell generator is representative of a cell making one type of part from

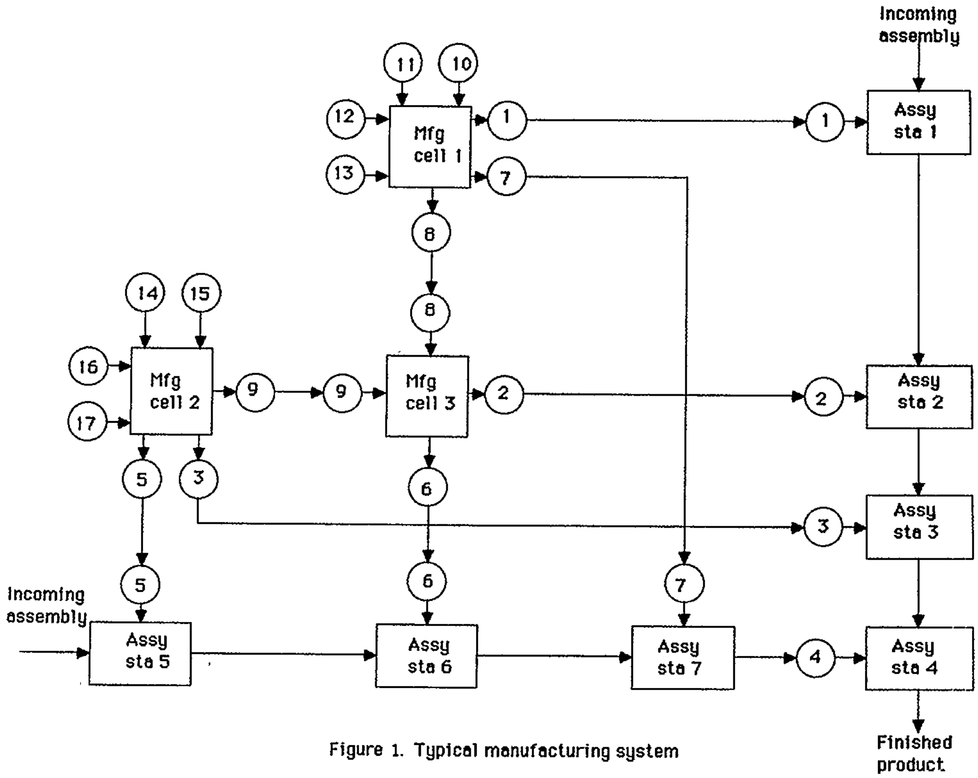

Figure 1. Typical manufacturing system

a given number of subparts. Parts are only made within the manufacturing cell when a signal is received from a manufacturing cell or an assembly station that a cart is empty and the empty cart has been moved by the whirlygig to the manufacturing cell.

Orders (i.e., signals) first wait in a queue until the manufacturing cell becomes available. Once the order seizes the cell, it waits in another queue until all the sub-parts are on hand to make a part. If there are insufficient sub-parts a signal is sent to have a full cart of sub-parts transferred to the manufacturing cell.

Once sufficient sub-parts are available, the manufacturing cell is seized and the parts made. An elapsed amount of time is simulated while the parts are made. Parts are made until the order is filled. The order then releases the manufacturing cell and the inventory (i.e., number of full carts of parts) is increased by one at the manufacturing cell stock point.

2.3 Inventory Transfer Generator

The inventory transfer generator is typical of a person moving carts between two stock points. Typical in a pull inventory system, an empty cart is returned to the manufacturing cell which signals the cell to begin making another cart of parts (an order). If a full cart of parts is available at the manufacturing cell stock point, the person returns the full cart back to the assembly station stock point. If no full carts are available the person waits.

3. MANUFACTURING SYSTEM SIMULATION

A typical manufacturing system (see Figure 1) was defined using the simulation generators and consists of a primary assembly line with four assembly stations. Feeding the assembly line is a subassembly line with three assembly stations. Each assembly station has an inventory stock point with an initial inventory. This inventory is defined as a number of carts with a fixed number of parts per cart. The inventory at assembly station 4 consists of the items from the subassembly line.

The system also contains three manufacturing cells with each cell making a defined type of parts which may be used in another manufacturing cell or used in one of the assembly stations. The manufacturing cells within the system operate in the pull mode. That is, a cart of parts is not made until a signal is sent from the appropriate assembly station that a cart is empty. Therefore, it is possible to evaluate the effect of work-in-process inventory on production.

3.1 Simulation Model

The simulation model was written using GPSS/PC (Minuteman 1986) and runs on the IBM/PC. Some model characteristics are:

- 23 GPSS blocks for assembly station generator
- 30 GPSS blocks for manufacturing cell generator
- 29 GPSS blocks for inventory transfer generator
- 125 Matrix savevalues for sending values to the generators.

A listing of the GPSS/PC code for the three generators is given in the appendix.

By using the simulation generators, the length of GPSS code for modeling the assembly and subassembly lines was quite short (see Figure 2). For example, the code for the assembly line consisted of a set of ASSIGN and TRANSFER blocks for each station. The ASSIGN block defines the station number 1-4. The TRANSFER block with the subroutine operator SBR transfers the transaction to the assembly station generator named ASM. The RTRN1 argument indicates the block for the returning transaction from the subroutine. The ASSIGN block setting parameter 9 equal to one was used to indicate the junction of an incoming subassembly.

The parameters describing each simulation generator are defined by a series of matrix savevalues. For example MSAVEVALUE PART(I,J) defines the initial WIP at station I. MSAVEVALUE STIME(I,J) defines the process time at station I. MSAVEVALUE ITEM(I,J) defines the sub-parts needed to make part I.

3.2 Experiments

The experimental objective was to evaluate selected system parameters by varying the number of full carts of parts at the various stock points and to then determine the minimum work-in-process inventory without impacting a given production rate.

It was assumed that the manufacturing system had one person or whirlygig to move the inventory or carts between the stock points. Table I gives the initial conditions at the stock points for each of the ten runs. All other parameters were held constant during the runs. Also, to simplify the system it was assumed that the inventory of sub-parts P_{10} - P_{17} (see Figure 1) was unlimited for the entire length of the simulation.

TABLE I. PARAMETERS VARIED WITHIN EACH RUN

Run	Number of full carts at each stockpoint	Number of parts per cart
1	1	1
2	1	2
3	1	3
4	1	4
5	2	1
6	2	2
7	2	3
8	2	4
9	3	1
10	3	2

The service times used for the manufacturing system are given in Table II. Arrival rates at the assembly and subassembly lines followed the negative exponential distribution. The processing times at each assembly station followed the normal distribution. The times to move carts between the stock points followed the uniform distribution.

```
********************************
   MAIN ASSEMBLY LINE          *
********************************
 GENERATE    60,FN$XPDIS
 ASSIGN      9,0               ;Non-junction.
 ASSIGN      2,1               ;Define station 1
 TRANSFER    SBR,ASM,RTRN1     ;Go to assembly generator
 ASSIGN      2,2               ;Define station 2
 TRANSFER    SBR,ASM,RTRN1     ;Go to assembly generator
 ASSIGN      2,3               ;Define station 3
 TRANSFER    SBR,ASM,RTRN1     ;Go to assembly generator
 ASSIGN      2,4               ;Define station 4
 ASSIGN      9,1               ;Junction
 TRANSFER    SBR,ASM,RTRN1
 TERMINATE   1
********************************
   SUBASSEMBLY LINE            *
********************************
 GENERATE    60,FN$XPDIS
 ASSIGN      9,0               ;Non-junction
 ASSIGN      2,5               ;Define station 5
 TRANSFER    SBR,ASM,RTRN1     ;Go to assembly generator
 ASSIGN      2,6               ;Define station 6
 TRANSFER    SBR,ASM,RTRN1     ;Go to assembly generator
 ASSIGN      2,7               ;Define station 7
 TRANSFER    SBR,ASM,RTRN1     ;Go to assembly generator
 ENTER       PA4,1             ;Add subassembly to stock
 TERMINATE
```

Figure 2. GPSS main program listing

Table II. Arrival and Service Times

Description	Distribution	Mean (sec)	Standard Deviation
Part arrival at assembly station 1	Exponential	60	
Part arrival at subassembly station 5	Exponential	60	
Process time at assembly stations 1-4	Normal	60	5
Process time at subassembly stations 5-7	Normal	60	5
Process time at manufacturing cell 1 and 2	Normal	10	1
Process time at manufacturing cell 3	Normal	30	4
Movement of carts between stock points	Uniform	4	4

The Conway technique (Conway 1962) was used to determine equilibrium. Before the model is run in a production environment, the model is set up to collect measurements on a periodic basis. Using GPSS, measurements were collected after every 100 transactions terminating from the system. After each replication, any of the collected statistics can be plotted as a function of time to give an indication of the behavior of the system. The Conway technique is to ignore all measurements until a measurement is neither a maximum nor a minimum value of the ignored set. This ignored set of measurements is then omitted from the statistics collection.

The average time to assemble a part was plotted for each replication of 100. The sixth replication was the first measurement that was neither a maximum nor a minimum of the previous set. Therefore, the first 500 transactions were required for the system to reach equilibrium. These transactions were then excluded from the collected statistics.

The GPSS commands to collect the measurements are:

```
REPORT REP1
START  100
RESET

REPORT REP2
START  100
RESET

REPORT REP3
START  100
   .
   .
   .
```

The REPORT command is a special GPSS/PC feature that causes an output file to be written after each START command. The RESET command clears all statistics.

After equilibrium has been determined, the following commands are used to collect the experimental results:

```
START 500,NP
RESET
START 500
```

The first 500 transactions are excluded from the collected statistics. The NP option suppresses the print option. The statistical tables are then RESET and the model run until 500 transactions or parts are completed.

3.3 Model Output

Table III gives the production rate per hour of finished product. The production rate was 45 per hour with one cart with a capacity of one at each stock point (Run 1). The production rate increased to 60 parts per hour with two carts with a capacity of two (Run 6). Interestingly the production rate also remained at 60 parts per hour with one cart of capacity two (Run 2) and two carts of capacity three (Run 7). Increasing the number of carts beyond two and the number of parts per cart beyond three did not increase production (Runs 3, 8 and 10).

TABLE III. PRODUCTION RATES WITH VARYING ASSEMBLY STATION INVENTORY

Run	Number of Carts	Parts Per Cart	Production/hour
1	1	1	45.3
2	1	2	60.4
3	1	3	54.5
4	1	4	56.3
5	2	1	51.2
6	2	2	60.2
7	2	3	59.6
8	2	4	58.6
9	3	1	49.7
10	3	2	60.6

Surprising was the high production rate for Run 2 which consisted of one cart with capacity two at each assembly stock point. Intuition suggests that a minimum of two carts are needed at each stock point with two parts per cart. That is, when the first cart is empty the manufacturing cell will begin making another cart of parts. While this is occurring, the assembly station can still use parts from the second cart. Hopefully the first cart will be filled and returned to the assembly station before the second cart is emptied.

Also surprising was the reduction in the production per hour when the cart capacity increased beyond two parts per cart. These two observations may indicate an underlying effect on production due to the increased time to manufacture a full cart of parts. That is, since the cart capacity increased, the delay waiting at an assembly stock point on a full cart of parts may also increase.

These high production rates for Runs 2, 6 and 10 can be explained by the queue statistics in Table IV. Table IV shows the average delay at an assembly station waiting for a full cart of parts. As Table IV indicates when cart capacity decreases the delay waiting on a full cart decreases. The result is increased production. Also, as cart capacity increases (Run 4) the delay waiting on a full cart increases. The result is decreased production.

TABLE IV. AVERAGE DELAY AT ASSEMBLY STATION WAITING ON FULL CART

Run	Station						
	1	2	3	4	5	6	7
1	20.1	7.8	19.3	2.1	20.3	7.5	15.1
2	0.0	0.1	0.2	0.2	0.0	0.0	0.3
3	1.2	0.3	1.6	0.0	0.5	0.4	0.6
4	4.1	0.2	3.2	0.0	3.1	0.2	4.6
5	8.2	11.0	4.6	0.0	8.2	11.3	4.8
6	0.0	0.0	0.0	0.3	0.0	0.0	0.0
7	0.0	0.0	0.0	1.1	0.0	0.0	0.0
8	0.0	0.0	0.0	0.2	0.0	0.0	0.0
9	2.0	13.2	0.3	12.7	2.1	13.1	0.5
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0

On the other hand, if the cart capacity is too small, the assembly line is starved for parts, and the delays increase (see Runs 1, 5 and 9 in Table IV). Therefore, it appears that the optimum production was achieved with one , two and three carts each with two parts.

Table V gives the utilization of the assembly stations for Runs 5 through 8. This utilization includes the time the station had been seized and was waiting for an available part. Overall, the assembly station utilization was relatively high and exceeded ninety percent for all runs. This line balance is anticipated since the mean assembly time at each station was the same.

TABLE V. ASSEMBLY STATION UTILIZATION

	Assembly Station						
Run	1	2	3	4	5	6	7
5	1.000	1.000	0.914	0.849	1.000	1.000	0.908
6	1.000	1.000	0.995	1.000	1.000	0.999	0.992
7	1.000	0.997	0.997	1.000	0.987	0.986	0.981
8	0.953	0.953	0.950	0.974	0.995	0.994	0.996

Table VI gives the utilization of the manufacturing cells for Runs 5 through 8. The cell utilization was approximately eighty-three percent for Run 5 and increased to over ninety-five percent for the remaining runs. The increase in cell utilization resulted from an increase in the production rate.

TABLE VI. MANUFACTURING CELL UTILIZATION

	Manufacturing Cell		
Run	1	2	3
5	0.833	0.833	0.836
6	0.973	0.971	0.985
7	0.961	0.963	0.976
8	0.956	0.950	0.963

4. CONCLUSIONS

The following general observations can be made from the simulation results using the simulation generators:

- o A rather complex manufacturing system can be readily modeled using the simulation generators.
- o The simulation generators can be easily defined using GPSS.
- o The real payoff in using the simulation generators is in modifying the GPSS simulation model or running various "what-if" scenarios.

The following observations can be made of the simulated manufacturing system:

- o Maximum production was achieved using one, two and three carts with two parts per cart.
- o As cart capacity increased beyond two parts the delay waiting on a full cart increased.
- o Small cart capacity of one part reduced production.
- o Assembly station utilization was relatively high and exceeded ninety percent for all runs.
- o Manufacturing cell utilization was also relatively high and exceeded ninety-five percent for the majority of the runs.

APPENDIX

The following listing is the GPSS/PC code for the three simulation generators.

```
****************************************
*       MANUFACTURING CELL             *
****************************************
MFG     ASSIGN      13,MX$CELL(P12,1)
        ASSIGN      17,2
        QUEUE       P13
PARTQ   ASSIGN      11,MX$ITEM(P12,P17)
        ASSIGN      10,MX$PART(P11,1)
        QUEUE       P10
        TEST GE     S*10,1
        LEAVE       *10,1
        SPLIT       1,FUSE1
        DEPART      P10
        TEST LE     P17,MX$ITEM(P12,1),FAC
        ASSIGN      17+,1
        TRANSFER    ,PARTQ
FAC     SEIZE       P13
        ADVANCE     V*16
        DEPART      P13
        RELEASE     P13
        SPLIT       1,DONE1
        TERMINATE
DONE1   ASSIGN      14,MX$SPART(P12,1)
        ASSIGN      15,MX$SCART(P12,1)
        ENTER       *14,1
        TEST L      S*14,MX$CSIZE(P12,1),FULLC
        TERMINATE
FULLC   LEAVE       *14,MX$CSIZE(P12,1)
        ENTER       *15,1
        TERMINATE
FUSE1   ASSIGN      32,P11
        TEST G      S*10,0,EMPTYC
        TERMINATE
```

```
***************************************
*         ASSEMBLY STATION            *
***************************************
ASM     ASSIGN      3,MX$STAN(P2,1)
        ASSIGN      4,MX$PART(P2,1)
        ASSIGN      6,MX$STIME(P2,1)
        QUEUE       P3
        SEIZE       P3
        DEPART      P3
        QUEUE       P4
        TEST GE     S*4,1
        SEIZE       P4
        DEPART      P4
        LEAVE       *4,1
        ADVANCE     V*6
        RELEASE     P4
        RELEASE     P3
        TEST E      P9,0,JUNCT
        SPLIT       1,AUSE1
        TRANSFER    P,RTRN1,1
JUNCT   ASSIGN      9,0
        TRANSFER    P,RTRN1,1
AUSE1   TEST LE     S*4,0,OUT
        ASSIGN      32,P2
        TRANSFER    ,EMPTYC
OUT     TERMINATE
***************************************
*         INVENTORY CONTROL           *
***************************************
EMPTYC  ASSIGN      12,P32
        ASSIGN      4,MX$PART(P32,1)
        ASSIGN      5,MX$CART(P32,1)
        SPLIT       1,ORDER1
        TEST GE     S*5,1
        LEAVE       *5,1
        ENTER       *4,MX$CSIZE(P32,1)
        TERMINATE
ORDER1  ASSIGN      7,MX$FGIG(P32,1)
        ASSIGN      16,MX$FTIME(P32,1)
        ASSIGN      36,MX$MTIME(P32,1)
        QUEUE       P7
        SEIZE       P7
        DEPART      P7
        ADVANCE     V*36
        RELEASE     P7
        SPLIT       MX$CSIZE(P32,1),MFG
GET1F   ASSIGN      8,MX$SCART(P32,1)
        QUEUE       P8
        TEST GE     S*8,1
        LEAVE       *8,1
        DEPART      P8
SEND1F  QUEUE       P7
        SEIZE       P7
        DEPART      P7
        ADVANCE     V*36
        RELEASE     P7
        ENTER       *5,1
        TERMINATE
```

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AUTHORS' BIOGRAPHIES

FAN TSONG TSENG is Assistant Professor of Management Science at the University of Alabama in Huntsville. He received his PhD in Operations Research from the University of Texas at Dallas. His current research interests include simulation expert system design, automation of manufacturing systems, and applied operations research.

BERNARD J. SCHROER is director of the Johnson Research Center and a research professor in the Department of Management Science at the University of Alabama in Huntsville. He has a PhD in industrial engineering from Oklahoma State University and is a registered professional engineer. Dr. Schroer is a member of IIE, SME/RI, SCS, AAAI, NSPE, and Sigma Xi.